Postprint: Numerical Simulation of Avalanche Processes in Arxian Gully, Western Tianshan Mountains Based on Air-Ground Coordinated Investigation

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Abstract

To accurately identify avalanche flow characteristics and flow regime information and comprehensively analyze their motion processes, this study obtains high-resolution aerial photography data based on UAV oblique photogrammetry technology. Taking the avalanche-prone Arxian Gully area as an example, the avalanche activity process is finely detected through field investigation and UAV remote sensing interpretation to determine RAMMS model input parameters. On this basis, different types of avalanche events are simulated and reconstructed, differences between traditional ground survey, UAV remote sensing interpretation results, and simulation results are comparatively analyzed, and avalanche activity processes under different types and different snow layer release conditions are discussed. The research results indicate: (1) The avalanche investigation and analysis system centered on oblique photogrammetry technology, which combines traditional ground survey methods with UAV remote sensing and numerical simulation for mutual verification, improves the accuracy of disaster development status assessment. (2) In mid-February, the snow thickness on the slopes of Arxian Gully approached the critical thickness value, and continuous snowfall caused snow layer instability triggering new-snow avalanches. At the time of investigation, it was still in the disaster gestation stage, snow layer cracks intensified deformation, and under wind action, the self-weight of snow cornices gradually increased with a tendency to exceed the snow's fracture strength, resulting in poor overall stability. (3) For slope-type avalanches with the snow accumulation platform above the slope as the potential release zone, the release volume can reach 8.2669\$×104*m*3, *themotiondurationisapproximately*128*s*, *andtheflowheightintheaccumulationzonereachesa*
s−1, *themaximumimpactforcecanreach*32.67*kPa*, *formingadepositwithanareaof*3369.7*m*2*andavolumeof*1.8
m3. Through mutual verification, slope-type avalanches are not released from

the snow accumulation platform, and there are differences between ground survey results and numerical simulation interpretation results. (4) The gully-slope composite avalanche involves fracture release of snow layers on the gully slope with a fracture depth of only about 60% of the critical thickness value, the avalanche duration is close to 300 s, the maximum flow velocity in the accumulation zone is 6.58 m・s-1, the maximum impact force is 17.97 kPa, the average deposit depth is 1.64 m, the affected area is 1178.5 m2, the deposit volume is 3107.76 m3, and ground survey results are consistent with numerical simulation results. The research results have improved the accuracy of avalanche event information acquisition to a certain extent, and can provide strong data support and scientific basis for future avalanche potential hazard prediction, risk avoidance, and disaster emergency response.

Full Text

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Numerical Simulation of Avalanche Processes in Aerxiangou, West Tianshan Mountains Based on Air-Ground Cooperative Investigation

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Abstract

To accurately identify avalanche flow characteristics and flow regime information and comprehensively analyze avalanche motion processes, this study employed UAV tilt photography technology to obtain high-resolution aerial data. Taking the avalanche-prone area of Aerxiangou as a case study, we conducted detailed detection of avalanche activity processes through field investigation and UAV remote sensing interpretation to determine RAMMS model input parameters. Based on this foundation, we simulated and reconstructed different types of avalanche events, comparatively analyzed differences among traditional ground surveys, UAV remote sensing interpretation results, and simulation outcomes, and explored avalanche activity processes under different types and snow layer release conditions. The results demonstrate that: (1) The avalanche investigation and analysis system centered on tilt photography technology, which combines traditional ground survey methods with UAV remote sensing and numerical simulation for mutual verification, improves the accuracy of assessing disaster development conditions. (2) In mid-February, the snow thickness on slopes in Aerxiangou approaches the critical thickness value, and continuous snowfall destabilizes the snow layer, triggering new snow avalanches. At the time of investigation, the area remains in the disaster gestation stage, with snow layer cracks showing intensified deformation. Under wind action, the self-weight of snow cornices gradually increases, showing a tendency to exceed the breaking strength of snow, resulting in poor overall stability. (3) For slope-type avalanches with a snow accumulation platform above the slope surface as the potential release area, the release volume can reach 8.2669\$×10ˆ{4}\$ m^{3}, with a movement duration of approximately 128 s. The flow height in the accumulation area reaches its maximum of about 3.55 m at 120 s, the maximum flow velocity reaches 18.34 m$\cdot$s^{-1}, and the maximum impact force reaches 32.67 kPa, forming an accumulation body with an area of 3369.7 m^{2} and a volume of 1.8525\$×10ˆ{4}\$ m^{3}. Through mutual verification, slope-type avalanches do not involve release from the snow accumulation platform, and discrepancies exist between ground survey results and numerical simulation interpretation results. (4) Trench-slope composite avalanches involve fracture release of the snow layer on the trench slope, with the fracture depth being only about 60% of the critical thickness value. The avalanche duration approaches 300 s, with the accumulation area covering 1178.5 m^{2}, an average accumulation depth of 1.64 m, a flushing-out volume of 3107.76 m^{3}, a maximum flow velocity in the accumulation area of 6.58 m$\cdot$s^{-1}, and a maximum impact force of 17.97 kPa. Ground survey results are consistent with numerical simulation results. These findings improve the accuracy of avalanche event information acquisition and can provide strong data support and a scientific basis for future avalanche potential hazard prediction, risk avoidance, and disaster emergency response.

Keywords: avalanche; unmanned aerial vehicle; oblique photography; numerical simulation; motion feature

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1 Introduction

Avalanches are severe natural disasters caused by the destabilization of slope snow under the synergistic action of meteorological factors, snow characteristics, and geological and geomorphological conditions. They not only hinder regional transportation, tourism, and agricultural and pastoral production but also threaten people's lives and property, creating enormous societal pressure. With the rapid economic development in mountainous areas, China has placed higher demands on avalanche prevention and control work. Avalanche investigation and research form the foundation for scientific and effective prevention, making it urgent to conduct avalanche studies to support decision-makers with more detailed and accurate survey data for avalanche risk assessment.

Avalanche trajectories and motion characteristics are key factors in disaster prevention and control. However, current investigations of large-scale avalanches are limited by harsh natural conditions, terrain constraints, and transportation accessibility in high-altitude mountainous regions. Traditional manual ground survey methods often cannot comprehensively and objectively describe avalanche motion trajectories accurately and consume substantial manpower and time resources. Therefore, there is an urgent need to develop new technologies that can rapidly, comprehensively, and precisely describe avalanche motion processes.

In recent years, UAV aerial photography systems have been increasingly applied in disaster investigation due to their numerous advantages, including high timeliness, high resolution, low cost, low loss, low risk, and repeatability. Researchers have demonstrated that UAV-acquired images provide more detailed and abundant geometric and semantic information for 3D visualization. Zhao et al. used high-resolution orthophotos and large-scale stereo orthophotos obtained from UAV low-altitude photography technology to model and analyze mine geological disasters, enabling fine detection of disaster activity processes and quantitative and qualitative analysis of disaster types, scales, losses, and hazards. Peng et al. found that UAV low-altitude photography technology can effectively identify spatial distribution patterns and development characteristics of disasters while clearly revealing deformation signs and disaster formation processes. Eckerstorfer et al. conducted aerial avalanche surveys using UAVs, extracting valuable information about flow characteristics and flow regimes from orthophotos of avalanche debris and generating snow avalanche surface digital elevation models. This data can be more effectively applied to avalanche dynamic modeling and research on snow depth spatial variability. Compared with traditional manual field surveys, these non-contact disaster information acquisition technologies offer significant advantages in accuracy, efficiency, and safety, providing more sufficient scientific basis for protecting people's lives and property and disaster emergency response.

In the field of avalanche motion process simulation, due to the suddenness and complexity of avalanche processes, most existing simulation models are based on empirical models and simplified physical models. These models primarily calculate characteristic values during the motion process. The Swiss Federal Institute for Snow and Avalanche Research developed the two-dimensional avalanche dynamic numerical model—Rapid Mass Movement Simulation (RAMMS)—based on the Voellmy model theory. This model considers the non-constant and non-uniform motion characteristics of flow height and velocity changes during avalanche motion, uses snow depth-averaged equations coupled with Random Kinetic Energy (RKE) model to consider mass and momentum conservation, and explains the random motion and inelastic interaction between snow particles, thereby better simulating various characteristic parameters during the motion process.

In summary, this study applies UAV tilt photography technology to avalanche investigation and research in Aerxiangou, West Tianshan Mountains, Xinjiang. Using aerial data to finely detect avalanche activity processes, identify avalanche flow characteristics and flow regime information, and generate high-precision DEM data, combined with field measurements to determine RAMMS model input parameters for avalanche motion process simulation. Through simulation and reconstruction of different types of avalanche events and comparative analysis of differences among traditional ground surveys, UAV remote sensing interpretation results, and simulation results, this study explores avalanche activity processes under different types and snow layer release conditions, providing strong data support and a scientific basis for future avalanche potential hazard prediction, risk avoidance, and disaster emergency response.

1 Study Area Overview

The Tianshan Mountains extend in a quasi-east-west direction with special topographic structures. Influenced by westerly airflow, the Ili River Valley and its surrounding mountainous areas in the West Tianshan region form a rich precipitation zone. Due to typical fold-fault block mountains, ancient cirques and nivation depressions are scattered throughout, where large amounts of snow can accumulate, making them avalanche-prone areas. Aerxiangou is located deep in the West Tianshan Mountains, featuring a medium-to-high altitude mountainous landform formed by intermontane basins and valleys developed along latitudinal tectonic mountains. The terrain on both sides of the gully shows significant relief, with steep mountain slopes generally ranging from 40° to 60° and ground elevations reaching 3500 m. The southeast side of the river valley has few avalanche traces in the forest, while the northwest side has exposed mountains with low vegetation coverage, belonging to a typical avalanche disaster gestation area. Avalanche investigations conducted in the winter and spring of 2022 revealed that nearly one hundred avalanches developed within a 14 km section in the main avalanche area, occurring frequently and intensively.

The snow conditions in Aerxiangou largely determine avalanche triggering and destructive power. By constructing a DZZ4-type regional automatic weather station to monitor snow condition changes during the winter and spring of 2022-2023, we obtained dynamic variation trends. For observation indicators with high variability such as air temperature and wind direction, a 0.25 s sampling method was adopted; wind speed used a 1-second sampling method; snow depth and solid precipitation used a 1-minute sampling method. The specific location and conditions of the weather station are shown in [Figure 1: see original paper].

Aerxiangou experiences deep winter snow cover with long duration, with the snowfall period extending from October to April of the following year. Snow accumulation begins when the average monthly temperature drops below 0°C starting in November, with the deepest average surface snow depth reaching 91 cm. In February, temperature shows obvious 回升, while prevailing winds appear in the valley and the average wind speed peaks during the snow period in February, reaching 2.87 $\mathrm{m \cdot s^{-1}}$, with maximum wind speeds up to 12 $\mathrm{m \cdot s^{-1}}$. Wind speed variations cause snowdrift-formed snow layers to exhibit significant changes in density and hardness, with stresses in the snow layer accumulating locally, thereby increasing snow layer instability. Additionally, during a snowfall event, the increase in new snow density (i.e., high-density snow overlying low-density snow layers) leads to increased snow layer instability. Under external forces such as wind and snowfall, the probability of avalanche outbreaks in the study area increases.

2 Methodology

2.1 Air-Ground Cooperative Investigation

2.1.1 Ground Investigation During traditional ground investigation, the survey area was divided according to avalanche types to determine key survey areas, general survey areas, and non-survey areas. Key survey areas refer to zones that meet avalanche disaster triggering conditions and significantly impact highways and important structures. Non-survey areas refer to zones where avalanche disasters do not affect highways or important structures. General survey areas refer to zones with poor avalanche disaster triggering conditions that may have minor impacts on highways and important structures (FIGURE:4). For key survey areas, field measurements were conducted to obtain actual avalanche disaster data, and UAV avalanche survey technology was further employed to interpret and supplement the investigation. A three-dimensional model was established based on aerial data to conduct systematic and comprehensive analysis of avalanche disaster points and potential hazard points within the survey area, identify avalanche types, recognize avalanche release zones, motion zones, and accumulation zones, and determine the spatial distribution status and quantity of disasters. On this basis, avalanche process numerical simulation was performed to compare and analyze the accumulation body with field observation ranges to evaluate simulation accuracy. Through mutual verification among 3D model interpretation, numerical simulation results, and field survey data, basic attribute information of disaster points was improved, and an avalanche disaster database was constructed to provide a basis for disaster prevention and control. The specific air-ground cooperative investigation flowchart is shown in [Figure 3: see original paper].

2.1.2 UAV Aerial Survey and Data Acquisition Based on ground survey zoning results, UAV avalanche surveys were conducted in key survey areas. Preparatory work included collecting meteorological data, fixed-point reconnaissance, and delineating flight areas. On this basis, flight routes were planned and relevant flight parameters were set. To ensure survey area integrity, a 10%-30% buffer zone was established. To maximize UAV aerial photography coverage, an optimal tilt photography angle of 45° was set according to the survey area and buffer zone size. By increasing photo overlap and shooting intervals, at least three overlapping images from different positions were ensured for all locations within the survey area, guaranteeing model detail clarity and data accuracy. UAV tilt photography technology obtains ground multi-angle texture images through fixed-point exposure using multi-lens tilt cameras, then processes them to generate real-scene 3D models. The generated Digital Elevation Model (DEM) and Digital Orthophoto Map (DOM) feature high precision and clear imaging, serving as reliable data sources for avalanche motion process simulation.

UAV tilt photography 3D reconstruction technology captures information from different surface features from one vertical and multiple tilted perspectives, obtaining detailed contour and texture information of facades to identify avalanche release zones, motion zones, and accumulation zones and determine avalanche spatial distribution status. During 3D reconstruction, aerial data can be preprocessed to solve problems such as image distortion and deformation, including using camera distortion parameters for image rectification and feathering and re-exposure processing to address exposure or color imbalance caused by weather conditions during aerial photography. Preprocessed aerial data is imported into multi-view 3D modeling software to obtain dense point cloud data, generate 3D models, and export DEM and DOM. Based on model results, UAV visual remote sensing interpretation is conducted to analyze avalanche spatial geographic attributes. The UAV avalanche disaster investigation technology flowchart is shown in [Figure 5: see original paper].

2.2 RAMMS Avalanche Process Simulation Principles and Input Data Acquisition

2.2.1 Model Simulation Principle Analysis The RAMMS model simulates avalanche flow processes in complex terrain. Its essence lies in considering the non-constant and non-uniform motion characteristics of flow height and velocity changes during avalanche motion based on the RAMMS model, using snow depth-averaged equations coupled with the RKE model to consider mass and momentum conservation, and explaining the random motion and inelastic interaction between snow particles. The model uses a Cartesian coordinate system to characterize average velocity U, assuming X and Y as horizontal coordinates fixed in the Cartesian coordinate system, and Z(x,y) as the mountain contour parameterized by X and Y. The independent variables X and Y represent terrain arc length, and coordinates X, Y, and Z form a surface-induced coordinate system. With time t variation, avalanche flow height H(x,y,t) (m) and average velocity U(x,y,t) ($\mathrm{m \cdot s^{-1}}$) also change. The average velocity U(x,y,t) relationship is as follows:

$$\mathbf{U} = \begin{pmatrix} U_x \\ U_y \end{pmatrix}, \quad \mathbf{U}^T = \begin{pmatrix} U_x & U_y \end{pmatrix}$$

where U_x is the flow velocity value along the X-axis, U_y is the flow velocity value along the Y-axis, $\mathbf{U}^T$ is the transpose of the average velocity matrix, and $\mathbf{U}$ represents the avalanche motion direction.

Due to the shallow fluid geometry of avalanches, the mass balance equation is used to solve for avalanche flow height H:

$$\frac{\partial H}{\partial t} + \frac{\partial}{\partial x}(HU_x) + \frac{\partial}{\partial y}(HU_y) = \dot{Q}$$

The model considers friction coefficients in two parts: the dry Coulomb friction coefficient μ proportional to normal stress N and the turbulent friction coefficient ξ. The friction resistance **S** (Pa) formula is as follows:

$$\mathbf{S} = \mu N \frac{\mathbf{U}}{|\mathbf{U}|} + \xi \rho g H \frac{\mathbf{U}}{|\mathbf{U}|}$$

where ρ represents density, g is gravitational acceleration, ϕ is the slope angle, h is flow height, and $\mathbf{u}$ is the velocity vector. Friction coefficients have a direct impact on the debris flow transport evolution process. When flow approaches stopping, μ dominates; when flow velocity is high, ξ dominates.

2.2.2 Determination of Snow Layer Fracture Depth Fracture depth refers to the average snow thickness that slides along the fracture after a certain thickness of snow layer in the avalanche release zone fails under gravity, temperature, and other factors, forming fractures perpendicular to the slope. According to the equilibrium conditions of slope snow cover, gravity on slope snow can be decomposed into stress parallel to the slope and normal pressure perpendicular to the slope. The underlying snow layer tends to slide down the slope under gravity. When the sliding force exceeds the resistance, an avalanche is triggered. This leads to the determination of critical snow thickness on slopes, as shown in formula (3). When slope snow thickness reaches the critical thickness value, the sliding force and resistance of the snow layer are in equilibrium. At this point, if snow thickness increases or snow layer stress distribution becomes uneven, snow layer settlement and collapse will occur. Therefore, this study uses critical thickness to determine snow layer fracture depth.

$$h_k = \frac{c}{\rho g(\sin\alpha - \cos\alpha\tan\phi)} + \frac{\tau}{\rho g\cos\alpha}$$

where h_k is slope snow thickness, c is cohesion between snow and slope surface, ϕ is the internal friction angle between snow and ground, ρ is snow density, α is slope gradient, and τ is shear strength. All variables in formula (3) are related to snow and slope characteristics. Based on the actual field conditions of the study area and the analysis results of physical and mechanical strength of different snow types obtained by Hu et al. in their study of seasonal snow physical properties in Tianshan Mountains, the values in formula (3) were determined (TABLE:1), where slope gradient is obtained through terrain analysis.

2.2.3 Determination of Friction Coefficients For friction coefficients (μ, ξ), RAMMS has two settings: constant and variable calculation modes. The constant calculation mode considers the avalanche motion area underlying surface to be in the same surface condition, using fixed μ and ξ values for the entire avalanche motion area (release zone, motion zone, accumulation zone). The friction coefficient values depend on the return period and avalanche volume. The variable calculation mode uses non-fixed μ and ξ values, considering different surface conditions in different altitude regions and applying different μ and ξ values. According to avalanche characteristics within the study area and combined with model parameter recommended values, appropriate values were selected for the study region.

Considering that avalanche motion bodies are composed of snow clumps and may carry granular debris and other materials, velocity fluctuations occur when moving in parallel or non-parallel slope directions. The RKE model provides real-time correction to better represent real-time avalanche motion characteristics. The modified dry Coulomb friction coefficient μ and turbulent friction coefficient ξ depend on R:

$$\mu = \mu_0 + k_\mu R, \quad \xi = \xi_0 + k_\xi R$$

where k_μ and k_ξ are the friction exponential growth rates for the average random kinetic energy density function, and R is the depth-averaged random kinetic energy.

2.2.4 Digital Elevation Model DEM is the most basic input data in RAMMS, accurately reflecting terrain features of the avalanche simulation area. Its resolution significantly impacts simulation results. Christen et al. and Buhler et al. used 2.5 m and 5 m grid resolutions for simulation, respectively, finding that different computational grid resolutions result in distribution differences in avalanche flow center accumulation. Buhler found that 2 m spatial resolution is sufficient for accurate simulation of large-scale avalanches, and simulation results show high consistency with actual conditions. Based on the study area size, computation time, and avalanche scale, and to ensure simulation accuracy, this study uses DEM obtained from UAV tilt photography aerial data at 2.0 m resolution as input data for avalanche process simulation.

2.3 3D Computational Model Establishment

Based on the high-precision DEM obtained from UAV tilt photography technology, ArcMap was used to complete terrain surface analysis, automatically identify suitable slope areas, delineate avalanche release zones, and locate forests and infrastructure. The specific procedure is as follows: (1) Create a map, import DEM, and create an environmental model. (2) Execute “Create Shapefile,” set the feature type as “Polygon,” unify the coordinate system as WGS_{{{1984}}*{{UTM}}*}{{{Zone}}_{{45N}}}, and delineate avalanche release zones based on automatic slope identification results, then overlay forest areas. RAMMS has two settings for friction coefficients: constant and variable calculation modes. Using constant friction values for calculation does not consider terrain undulation and forest areas, while using variable friction values requires classification and setting of friction values based on terrain data. Therefore, forests, infrastructure, and other areas need to be divided to facilitate classified friction value setting. (3) Import the Shapefile file into the avalanche dynamics numerical simulation software—RAMMS, then determine simulation software input parameter values based on preliminary field survey and measurement data. Finally, output the avalanche 3D computational model.

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3 Avalanche Investigation and Process Simulation in Aerxiangou

3.1 Avalanche Information Extraction

According to field information extraction, an avalanche occurred on the steep mountain body on the north side of the highway at K14+200 on February 15, 2023. Investigation revealed exposed rocks on the steep mountain body north of the highway, with obvious surface snow sliding traces. The avalanche released from the steep slope, rushed out across the highway, and the braking zone was located outside the hard shoulder on the south side of the highway. Analysis of the avalanche accumulation area at K14+200 (FIGURE:6) shows a relatively uniform accumulation body profile structure. Snowdrift traces exist on the mountain slope. Field measurements indicate a snow density of 434 $\mathrm{g \cdot cm^{-3}}$ and a height of about 1.7 m. From the field situation, the avalanche release zone may be located on a relatively low and small local slope surface. The avalanche debris has small particle size and is mainly powdery, with relatively uniform profile snow structure, belonging to a new snow avalanche.

Based on orthophoto images, a 3D real-scene model was established (FIGURE:8). The avalanche at K14+200 is a slope-type avalanche, accounting for about 1/3 of the highway width. The slope surface above has two natural snow accumulation platforms with catchment areas between 0.58239$×10^{4}$ and 1.3108$×10^{4}$ m^2, presenting a shape of steep upper part and gentle lower part. The upper steep slope reaches gradients above 45°, with little snow on the slope surface and exposed ground. Snow mainly accumulates on the lower gentle slope with gradients of 30°-45°. The shortest distance from the snow platform to the slope bottom is 510 m, and the longest is 594 m. The main causes of slope-type avalanches are: (1) Snow on the local slope reaches critical thickness, causing snow layer instability, with wide avalanche impact range and large accumulation area snow volume, but overall impact force and flow velocity are relatively small. (2) Snow layer instability on the upper snow platform leads to large snow release volume, with two snow platforms sharing the same motion zone, easily causing simultaneous release from both snow accumulation areas. The avalanche flow has a confluence point. Considering snow entrainment effects, it is prone to cause instability of snow on gentle slopes, posing greater danger and wider impact range.

According to aerial data interpretation, snow cornices and snow layer cracks exist in this area. Using UAV Real Time Kinematic (RTK) aerial measurement technology, the largest two snow cornices in the slope-type avalanche were found to be 80-150 m long, developing along the ridge in a north-south direction. Snow layer cracks develop parallel to the snow cornices, with the longer crack reaching 155.41 m and the shorter 144 m, with obvious sliding traces around the cracks. Vertical cracks appear on the lower slope, extending to the slope bottom with a length of 254.28 m (FIGURE:9). During the disaster interpretation process of the trench-slope composite avalanche, multiple snow cornices were found in the catchment area, with the largest being 191.88 m long, developing in an east-west and north-south direction. Snow layer cracks develop parallel to the snow cornices, with lengths of 184.38 m. Multiple cracks and avalanche sliding traces are visible in the release zone.

Based on comprehensive analysis of interpretation results and ground surveys, the study area remains in the disaster gestation stage. If continuous snowfall is followed by sustained temperature rise, snow cornices and cracks will show intensified deformation trends, potentially leading to wet snow slab avalanches. High water content in snow layers results in large ejection distances, posing greater threats to the environment and infrastructure. Additionally, such avalanches can easily entrain soil during collapse, causing soil loss.

3.2 Model Construction and Disaster Interpretation

3.2.1 UAV Aerial Survey A DJI M300 UAV equipped with a Zenmuse P1 camera was used for aerial photography, covering a mapping area of 8.9256\$×10^{4}\$ m^2 with a flight time of about 32 minutes and 2 flight routes (FIGURE:7). Flight parameters are shown in TABLE:3. Due to different resolutions at high and low altitudes, the image ground resolution ranges from 0.05 to 0.10 m.

3.2.2 Data Processing and Disaster Interpretation Agisoft Metashape Professional software was used to process aerial data and generate a 3D real-scene model. Processing steps included photo alignment, dense point cloud generation, mesh generation, and texture generation. Orthophoto images were generated from dense point cloud data. Based on the orthophoto images, combined with ground survey conditions and terrain judgment, K14+200 was identified as a slope-type avalanche, while K14+900 belongs to a trench-slope composite avalanche. The upper release zone of the latter is trench-developed, wide at the top and narrow at the bottom, with the widest point exceeding 300 m and the narrowest point less than 100 m. The snow catchment area is large, with an overall catchment area reaching 38124.0 m^2. The straight-line distance from the release zone to the slope bottom is nearly 700 m, with large elevation difference. Measured slope gradients of the catchment area range from 26° to 35°, providing good snow storage conditions. Avalanche occurrence is mainly due to snow layer instability on both sides of the trench-type mountain body that collects in the trench. The wide upper trench body allows large snow collection volume, while the narrow lower part causes the avalanche to diverge left and right after rushing out onto the slope (FIGURE:9).

3.3 Avalanche Process Simulation and Analysis

After completing preliminary work, model input parameters were determined based on ground survey and UAV aerial data, then imported into RAMMS for model calculation of slope-type and trench-slope composite avalanches in the study area to analyze disaster activity characteristics. This study considers the maximum hazard scenario, i.e., maximum avalanche volume (full-layer fracture of slope snow), assuming critical thickness equals fracture depth.

Slope-type avalanche: $h_k = \frac{c}{\rho g(\sin 45° - \cos 45° \times 0.22)} \approx 0.6$ m

Trench-slope composite avalanche: $h_k = \frac{c}{\rho g(\sin 35° - \cos 35° \times 0.22)} \approx 0.84$ m

Considering that the slope-type avalanche in this study belongs to non-trench terrain, and the underlying surface of the avalanche motion area (release zone, motion zone, accumulation zone) is consistent (eroded structural mountainous area), friction coefficients use constant calculation mode. The trench-slope composite avalanche flows through channels, gullies, and valley flat areas, so friction coefficients use variable calculation mode. Therefore, friction coefficients for this avalanche simulation need to be classified and selected based on terrain characteristics and model reference values. Specific friction coefficient reference values are shown in TABLE:4.

3.3.1 Slope-Type Avalanche Simulation Results and Analysis Simulation results show that with the snow accumulation platform above the slope surface as the release zone, the avalanche release volume reaches 8.2669×10^{4} m^3. The avalanche motion direction mainly follows the slope surface, with concentrated avalanche flow and few tributaries. The accumulation area distribution is concentrated with relatively concentrated impact range. Two snow accumulation platforms share the same motion zone, releasing continuously under mutual influence, with the avalanche flow having a confluence point, consistent with the 3D real-scene model interpretation results. However, the resulting accumulation area distribution is concentrated and continuous, different from the dispersed accumulation area layout found during ground surveys. This indicates that recent slope-type avalanches did not involve release from the snow accumulation platform.

Considering the maximum avalanche volume scenario (full-layer fracture of snow layer), the avalanche flow motion duration is only 128 s. The maximum accumulation height is located within the river valley, reaching 3.55 m. The maximum flow velocity is 18.34 m $\cdot$ s^{-1}, and the maximum impact force is 32.67 kPa. The snow accumulation volume is approximately 1.8525×10^{4} m^{3}, affecting an area of about 3369.7 m^{2}. The avalanche flow reaches the highway within 120 s, with the braking zone located outside the hard shoulder on the highway's south side. According to terrain distribution, the accumulation body presents a cone shape with high middle and low periphery. From [Figure 10: see original paper], the accumulation area flow height reaches maximum at about 120 s, while the maximum flow velocity occurs at 128 s. A cross-section of the accumulation body was obtained along the highway, and the accumulation body morphology was reflected by the cross-section accumulation height. Influenced by slope morphology, a continuous cone-shaped accumulation body with high middle and low periphery was formed, consistent with ground survey accumulation morphology and aerial photography interpretation results. However, under full-layer fracture conditions, the average accumulation height in the accumulation area is 2.5 m, which does not match the measured average cross-section depth of 1.71 m from field surveys. This discrepancy is related to the release volume. In the simulation process, the snow volume in the accumulation area is controlled by friction coefficients and release volume. When the underlying surface is in the same surface condition, friction coefficients are identical, but different release volumes have significant impacts on the avalanche's runout distance and accumulation volume.

3.3.2 Trench-Slope Composite Avalanche Simulation Results and Analysis Considering the maximum avalanche volume scenario (full-layer fracture of snow layer), the trench-slope composite avalanche body initiates at an altitude of 2988 m, with a release volume of 7.6071×10^{4} m^{3}. It collapses from the slope surface, flows out along the wide-top and narrow-deep trench body, then spreads out in a fan shape along the slope surface. After 256 s, it begins to accumulate at an altitude of about 2229 m and stops accumulating after 300 s, forming an accumulation area of 1369.7 m^{2} with a volume of approximately 11717 m^{3}. Due to terrain factors, the accumulation area distribution is mainly controlled by the lower slope surface. In motion characteristic analysis, reduced fracture depth leads to decreased release volume, accumulation volume, maximum accumulation height, maximum accumulation area flow velocity, and maximum accumulation area impact force, while the accumulation area shows small overall variation amplitude.

To make accumulation area simulation results more consistent with ground survey conditions, single-factor analysis was used to conduct avalanche numerical simulations under different fracture depths, reducing fracture depths by 1/3 and 2/3 respectively (fracture depths of 0.67 m and 0.34 m). Simulation results show that when snow layer fracture depth is reduced by 1/3, the avalanche flow accumulation area impact range is 1299.5 m^{2}, average accumulation depth is 2.27 m, flushing-out volume is 4578.22 m^{3}, maximum accumulation area flow velocity is 10.24 m $\cdot$ s^{-1}, and maximum impact force is 21.42 kPa. When snow layer fracture depth is reduced by 2/3, the avalanche accumulation area impact range is about 1178.5 m^2, average accumulation depth is 1.64 m, flushing-out volume is 3107.76 m^3, maximum flow velocity is 6.58 $m \cdot s^{-1}$, and maximum impact force is 17.97 kPa. These three simulations show significant differences in avalanche release volume. Compared with full-layer fracture, fracture depth reduction by 2/3 results in later arrival at the accumulation area but the longest duration, approaching 300 s, while fracture depth reduction by 1/3 arrives at the accumulation area after 275 s, with both durations longer than full-layer fracture. The maximum snow thickness in the accumulation area forms later (at 300 s), mainly related to avalanche flow self-weight.

Comparison between observed values and simulation results shows that fracture depth reduction by 2/3 yields an average accumulation depth of about 1.64 m, similar to field accumulation body measurement results. The maximum flow velocity in the accumulation area reaches 6.58 $m \cdot s^{-1}$, and the maximum impact force is about 17.97 kPa, with maximum motion characteristic values sufficient to cause destructive damage to carriers and seriously threaten lives and property under severe conditions.

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4 Conclusions

Based on the air-ground cooperative investigation scheme for avalanche process numerical simulation and motion characteristic analysis, this study draws the following conclusions:

1) The avalanche disaster air-ground cooperative investigation system centered on UAV tilt photography combines traditional ground survey methods with UAV remote sensing interpretation and numerical simulation results for mutual verification, improving the accuracy of avalanche disaster development status assessment and compensating for subjectivity in excessive reliance on empirical value judgments.

2) In mid-February, under continuous snowfall conditions in Aerxiangou, West Tianshan Mountains, slope snow thickness approaches the critical thickness value, and snow layer instability triggers new snow avalanches. During the investigation, avalanches had already occurred and the area remains in the disaster gestation stage, with snow layer cracks showing intensified deformation trends. Under wind action, snow cornice self-weight gradually increases, showing a tendency to exceed snow breaking strength, resulting in poor overall stability with the possibility of large-scale avalanches under external forces such as snowfall and wind.

3) For slope-type avalanches with snow accumulation platforms above the slope surface as potential release zones, the release volume can reach 8.2669$×10^{4}$ m^3, with a motion duration of about 128 s. The flow height in the accumulation area reaches its maximum of about 3.55 m at 120 s, the maximum flow velocity reaches 18.34 $m \cdot s^{-1}$, and the maxi-

mum impact force reaches 32.67 kPa. The accumulation volume reaches 1.8525$×10^{4}$ m^3, affecting an area of 3369.7 m^2. Through mutual verification, slope-type avalanches do not involve release from the snow accumulation platform, and discrepancies exist between ground survey results and numerical simulation results.

4) Trench-slope composite avalanches were simulated under different fracture depths. The accumulation body morphology forms a continuous cone shape with high middle and low periphery under slope influence, consistent with field ground survey and aerial photography interpretation results. When snow layer fracture depth is reduced by 2/3, the avalanche duration approaches 300 s, the accumulation area covers 1178.5 m^2 with an average accumulation depth of 1.64 m, the flushing-out volume is 3107.76 m^3, the maximum flow velocity in the accumulation area is 6.58 $\text{m} \cdot \text{s}^{-1}$, and the maximum impact force is 17.97 kPa. Therefore, trench-slope composite avalanches involve fracture release of the trench-slope snow layer with fracture depth being only about 60% of the critical thickness value. Ground survey results are consistent with numerical simulation results.

These results improve the accuracy of avalanche event information acquisition and can provide strong data support and a scientific basis for future avalanche potential hazard prediction, risk avoidance, and disaster emergency response.

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Note: Figure translations are in progress. See original paper for figures.